Murmur-adaptive compression technique for phonocardiogram signals

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As mobile and wearable health technologies have evolved, constant monitoring of bio-signals from patients has become important for accurate diagnosis using mobile and remote health services. As the need for constant monitoring of bio-signals increases, the amount of bio-signal data also increases, therefore an efficient compression method for specific bio-signals should be developed. In contrast to other types of signals, bio-signals contain important diagnostic information that should not be removed during compression. An effective compression algorithm for phonocardiogram (PCG) signals that contain important diagnostic information (murmur) is proposed. In this algorithm, the murmur is first estimated, then an adaptive thresholding scheme is applied in the wavelet domain to the normal portions and the murmur portions of PCGs depending on the murmur estimates during compression. Although other conventional compression methods result in substantial loss of murmur information, the proposed method is able to keep most of the murmur information in compressed PCGs.

Introduction: The recent development of telemedicine and mobile technologies has enabled the constant monitoring of an individual's phonocardiogram (PCG), automated auscultation, as well as archiving and transmission of PCGs between patients and hospitals or health service providers. However, the constant monitoring of PCGs on a daily basis requires a large amount of disk space storage. Therefore, an appropriate compression method for PCGs should be developed.

Compression techniques based on wavelet transformation (WT) are efficient methods of analysing and compressing signals, especially when the signals change frequency with time [1, 2]. Recent literature on PCG compression has shown that wavelet-based methods outperform conventional audio compression techniques [3]. Most WT-based methods use a wavelet thresholding scheme to keep a certain percentage of the original signal energy [3–5]. With these methods, a threshold value is computed to retain a predefined percentage of the original signal energy (*RtEn*). These methods work well and outperform other conventional audio compression techniques as demonstrated in [3]. However, when it comes to abnormal PCGs that contain murmurs, we found that the compressed signals often sacrifice the murmur sounds, which contain important diagnostic information. Therefore, we propose a murmur-adaptive WT-based compression method that minimises the loss of the diagnostic information of murmurs.

Proposed method: Based on the previously published WT compression method [3], our proposed algorithm incorporates a murmur estimation process that finds murmur-related signals and applies an adaptive thresholding scheme based on whether the signal is a normal state or a murmur state. The overall procedure of the proposed method consists of the following steps:

Step 1: WT of the PCG signals.
Step 2: <MURMUR estimate> Find the murmur-related signal portions:
Step 2–1: Select murmur-related wavelet subbands (mostly in the high frequency bands).
Step 2–2: Hilbert transform to obtain the envelope of wavelet coefficients in these murmur-related wavelet subbands.
Step 2–3: Determine the murmur-related signal locations by analysing the envelope information.
Step 2–4: Find all wavelet coefficients in these murmur-related signal locations and apply these to all wavelet subbands.
Step 3: Adaptive thresholding of the wavelet coefficients in PCG signals:
Step 3–1: Thresholding of coefficients to keep *RtEn*.
Step 3–2: Retain coefficients in the murmur-related signal locations.
Step 4: Compression of the non-zero wavelet coefficients vector, using zero removal, linear quantisation and Huffman coding [3].
Step 5: Compression of the significance map, using zero removal, run length encoding and Huffman coding [3].

The proposed method introduces the murmur estimation process in step 2 to keep murmur information in the compressed PCG. Fig. 1 shows examples of wavelet decomposition for a normal and an abnormal PCG. The abnormal PCG in Fig. 1*c* contains a murmur in it as indicated by the dotted circle, and its wavelet decomposition in Fig. 1*d* clearly indicates the presence of a murmur in the highpass subbands. Since the murmur manifests itself in these highpass subbands, the murmur estimation is also performed in these same subbands. A Hilbert transformation [6] is applied to the coefficients in these subbands to extract the envelope of coefficients, $e(t)$, as in (1)

$$e(t) = \sqrt{w^2(t) + \hat{w}^2(t)} \qquad (1)$$

where $w(t)$ is the original wavelet coefficients and $\hat{w}(t)$ is the Hilbert transformation of $w(t)$. The murmur-related wavelet coefficients are determined by analysis of this envelope: its energy level should be above a threshold, its size should be large enough to be considered a murmur, and it should satisfy a certain length of continuity to distinguish it from noise. Details of the envelope analysis are not included here due to length and it being beyond the scope of this Letter.

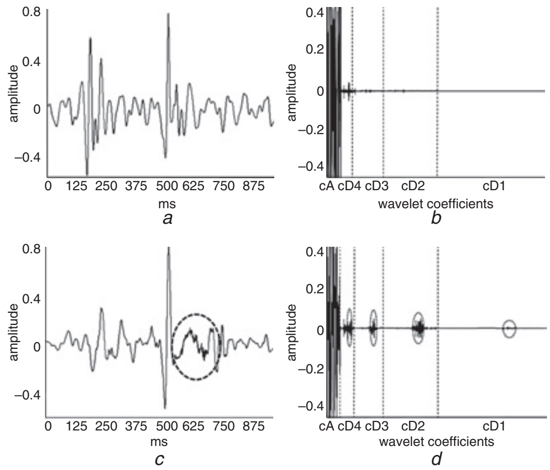

Fig. 1 *Normal and abnormal PCG signals: normal PCG signal in time domain (Fig. 1a) and in wavelet domain (Fig. 1b), abnormal PCG signal that includes murmur (indicated by dotted circle) in time domain (Fig. 1c) and including murmur in wavelet domain (indicated by dotted circles) (Fig. 1d)*

Once the murmur-related coefficients and their temporal locations are estimated using highpass subbands, all coefficients corresponding to these temporal locations in all the wavelet subbands are considered to be murmur-related coefficients. During adaptive thresholding, these coefficients are retained and others from the normal signal portions are thresholded using the same thresholding scheme as in [3] to keep *RtEn*.

After the murmur-adaptive thresholding of all wavelet coefficients is completed, the non-zero wavelet coefficients vector is compressed using zero removal, linear quantisation and Huffman coding. In addition, the significance map is compressed using zero removal, run length encoding and Huffman coding [3].

We applied our proposed method to multiple real PCG datasets and analysed the results. The compression rate (CR) and per cent root-mean-square difference (PRD) were used to evaluate our proposed method

$$\mathrm{CR} = \frac{S_o}{S_c} \qquad (2)$$

$$\mathrm{PRD} = \sqrt{\frac{\sum_{i=1}^{N}\left(x_i - x_i'\right)^2}{\sum_{i=1}^{N}\left(x_i\right)^2}} \times 100 \qquad (3)$$

where S_o is the size of the original PCG signal and S_c is the size of the compressed one including the significance map information. x_i is the original signal, x_i' is the recovered signal and N is the length of signal samples. Furthermore, a subjective assessment was performed using MUSHRA listening tests [7] to confirm the effectiveness of our proposed method.

Experimental results: We applied our proposed method to 60 real PCG records (16 bits, mono and 4000 Hz) obtained using a stethoscope (3M Littman Electronic Stethoscope Model 3200). This dataset includes many different cases covering normal signals and several different types of murmurs. The optimal parameters for compression were selected experimentally in our study with the wavelet mother function of *Daubechies7* and a WT decomposition level of 4.

We compared the proposed method with the non-adaptive compression method at different fixed CR levels. Fig. 2 shows a PRD comparison at CRs ranging from 5 to 15. The PRDs were evaluated over the entire PCG spans and averaged from 60 cases. The proposed method resulted in slightly higher PRDs than those made using the non-adaptive method, these differences were not however significant. In contrast, when PRDs were evaluated only over the murmur-related portions, the differences became significant, especially at moderate and high CR levels, as shown in Fig. 3.

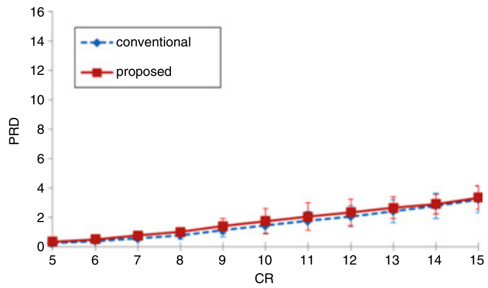

Fig. 2 *PRD values evaluated over entire PCG signal spans, averaged from 60 PCG compressions with conventional non-adaptive method and proposed method at different CRs. Differences were not significant*

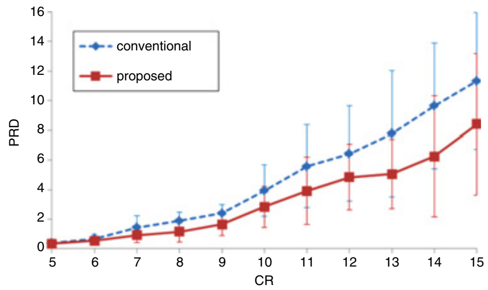

Fig. 3 *PRD values evaluated over murmur-related portions only. Differences became significant, demonstrating advantage of proposed method for retaining murmur information*

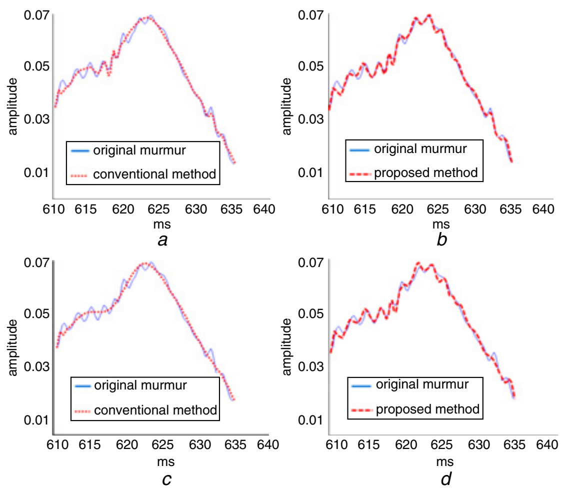

Fig. 4 *Loss of murmur information due to compression (only murmur portions are displayed for both original and compressed PCGs). Solid, dotted and dashed lines represent original murmur segments, compressed versions with conventional and proposed methods, respectively, at CRs of 10 (upper row) and 15 (bottom row)*

Fig. 4 shows how well the proposed method retains murmur signals compared with the conventional method. The dotted lines for the conventionally compressed PCG resulted in significant losses and distortion of the original murmur signals (solid lines). In contrast, the proposed method (dashed lines) was able to retain the murmur signals even at high CRs of 10 (upper low) and 15 (bottom row).

Figs. 3 and 4 show the distinct advantages of the proposed method in retaining murmur information in compressed PCGs. However, since more bits are adaptively assigned to the murmur portions compared with the conventional method at a fixed CR, less bits tend to be assigned to the normal portions of PCGs, which result in slightly higher PRDs for the proposed method when evaluated over the entire scan of PRDs, even though the difference is not significant, as shown in Fig. 2. Because of this, we investigated how these slight differences in overall PRDs affected the subjective quality of PCG sounds. We adopted the MUSHRA listening test (multi-stimulus test with hidden reference and anchor), a subjective assessment method for audio coding systems [7]. Five highly educated researchers with years of experience listening to PCGs participated in the MUSHRA tests.

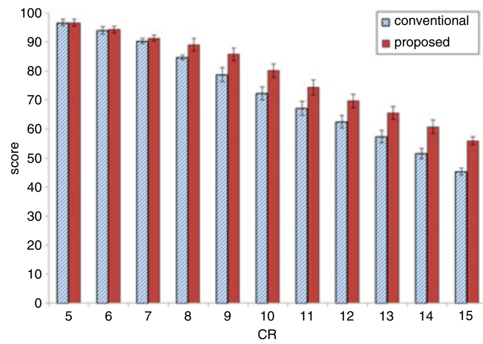

Fig. 5 *Subjective assessment of conventional and proposed compression methods using MUSHRA listening tests*

Fig. 5 shows the results from the MUSHRA listening tests. It is clear that the compressed PCGs, made using the proposed method, received higher scores than those made with the conventional method over all CR levels. As the CR level increases to over 7, our proposed method outperforms the conventional method with significant score differences. This result suggests that the small differences in PRDs observed in Fig. 2 do not affect the overall quality of compressed PCGs but the significant differences in PRDs over the murmur portions have more impact on the overall sound of the compressed PCGs.

Conclusion: We have proposed an efficient murmur-adaptive compression technique for PCG signals in order to retain diagnostically important murmur information in the compressed PCGs. Using a murmur estimation process and an adaptive thresholding scheme on the wavelet coefficients, the proposed algorithm was able to produce superior compression results compared with the conventional method. Both quantitative analysis and subjective assessments of real PCG datasets demonstrated the advantage of our proposed method.

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One or more of the Figures in this Letter are available in colour online.

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